A Real-Options Approach for NASA Strategic Technology Selection

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Abstract. In this paper, we examine the use of real options valuation in the context of prioritizing advanced technologies for NASA funding. Further, we offer a set of computational procedures that quantifies the option value of each technology. Other researchers have applied a real options framework to private sector investments. In the case of NASA investments in advanced technologies, the underlying products, which must be used to justify the investments, are nearly pure public goods—in particular, space-related scientific results and discoveries to be shared worldwide. As in the private sector, uncertainty plays a significant role in the motivation to use real options in NASA. Uncertainty in NASA technology investments can be classified as development risk and programmatic risk (whether missions using the technology will actually fly). The latter might be called the technology's "market risk."

The approach was tested on two real-world technologies applicable to the Mars Sample Return (MSR) series of missions from 2003 to 2013. One, low temperature and mass propulsion, was identified as cost-reducing and the other, autonomous Mars-orbit rendezvous and docking, as mission-enabling.

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1.0 Introduction

In this paper, we examine the use of an option pricing approach in the context of selecting those advanced technologies that should receive scarce NASA funding. Further, we offer a set of computational procedures that quantifies the option value of each technology.

Option pricing has already been applied to a variety of investment decisions by firms. When option-pricing applications do not involve financial instruments, the term, "real" options, is used. Real-option calculation methods have been developed for real estate and electric power investments, and for product development in the pharmaceutical and entertainment industries.[1] Company research and development (R&D) funding can be thought of as buying an option to produce new products, without incurring the obligation to do so unless proved economically viable. *In option pricing thinking, technology developments are treated as assets whose payoffs are uncertain, but that have the characteristic of enabling potentially spectacular returns with limited losses.*

The motivation for using real option pricing to value technology developments in NASA is the same as in the private sector. In the words of Robert C. Merton [1998] from his December 1997 Nobel Lecture: "the future is uncertain . . . and in an uncertain environment, having the flexibility to decide what to do after some of that uncertainty is resolved definitely has value. Option-pricing theory provides the means for assessing that value."

In the private sector, the ultimate products of technology have the important characteristic that they are private goods that go through ordinary markets. As such, there is a substantial likelihood that consumer demand information is available with which various

[1] See, for example, Faulkner [1996], Luehrman [1992], Majd and Pindyck [1987], Nichols [1994], and Zinkhan [1991].

investment outcomes can be converted into monetary units. In the case of NASA investment in advanced technologies, the ultimate products, which must be used to justify the investments, are space-related scientific results and discoveries to be shared worldwide. A formal option-pricing calculation method for NASA technology investments must consider the public goods aspects of the ultimate products and the problem of valuing their benefits to society. It must also treat the underlying uncertainties on both the cost and benefit sides.

1.1 Advanced Technology Investments in NASA

At NASA, technologies are categorized by their maturity, which is defined by a qualitative measure called the Technology Readiness Level (TRL). The nine-point TRL scale is described in Table 1 below.

Table 1—Technology Readiness Level Definitions

TRL	Definition
Level 1	Basic principles observed and reported
Level 2	Technology concept and/or application formulated
Level 3	Analytical and experimental critical function and/or characteristic proof-of-concept
Level 4	Component and/or breadboard validation in laboratory environment
Level 5	Component and/or breadboard validation in relevant environment
Level 6	System/subsystem model or prototype demonstration in a relevant environment (Ground or Space)
Level 7	System prototype demonstration in a space environment
Level 8	Actual system completed and "flight qualified"
Level 9	Actual system "flight proven" through successful mission operations

NASA technology investments are designed to raise the TRL for those technologies supporting NASA missions. Most of NASA's technology investment efforts are short-term, low-risk mission-pull development, but about 20% of its technology funding goes into long-range, higher-risk (generally, low-TRL) technology push work that supports a wide spectrum of potential future missions. The selection of those technologies to fund is largely made by expert judgment.[2] The critical issue, then, is whether the technology portfolio selected this way is the most efficient. In particular, is the 80/20 allocation the right mix, and are there long-range, higher-payoff technologies that are not being funded?

The application of portfolio methods and real-option pricing would appear to address both questions. In this paper, we will concentrate on developing the real-options approach for those long-range, higher-risk technology investments. These investments generally are designed to move a technology with a TRL < 6 up to a TRL = 6, at which point a funded NASA mission can assume responsibility for its full development. Using the formal three-tiered structure proposed by Hauser (1998), these investments fall into Tier 1 (Basic Research Explorations) and Tier 2 (Development Programs to Create Core Technological Competence). "Productizing" a specific technology falls into Tier 3 (Applied Engineering Projects), and is accomplished during the development phase of a funded NASA mission that uses the technology.

1.2 Types of Uncertainty in NASA Technology Investments

Uncertainty in NASA technology investments can be classified as development risk (cost, schedule, and technical performance), and programmatic risk (whether missions using the

[2] Often committees of experts attempt to subjectively integrate several elusive high-level factors. We believe that the use of expert judgment in this problem should be at a lower level, where direct experience can best be applied.

technology will actually fly). The latter might be called the technology's "market risk." A technology's option value must ultimately depend on its market success as well as its development success. To be credible, any real-options formula must reflect these types of uncertainty and capture them quantitatively. A brief description of these uncertainties in a typical NASA technology investment is warranted.

Development risk is more easily understood. Each long-range NASA technology investment faces uncertainty about the cost of bringing it to TRL = 6 by a particular date, even if its development team is completely successful. There may be several reasonable paths to achieving TRL = 6, each with its own pace, resource requirements, and risks. Generally, by increasing the amount of resources, the date can sometimes be moved forward and the probability of a successful development increased. Indeed, one can picture a surface representing (at each point in time) the feasible combinations of the probability of development success, development time, and expected development cost. A technology's option valuation must explicitly identify the technology's delivery date, and take into account the cost probability density and probability of meeting its technical performance.

Programmatic risk arises because how many missions and which missions NASA will choose to fly in the future is not known with certainty. Mission "roadmaps" exist, along with strategic plans directed at particular space science and exploration goals. Missions (conceptual versions, at least) in the current roadmaps have a higher probability of being flown than missions not currently on such roadmaps. However, missions on the roadmap could conceivably be replaced by new missions, not currently planned; and new missions could be added to the roadmap in future years. One reason for this uncertainty is that future NASA budgets and their allocation are not fully predictable.

Whether any particular future mission flies is linked to its perceived value (as measured by society's willingness-to-pay) at some future date. That value could be substantially greater than we now perceive or it could be much less, because serendipitous science discoveries from earlier (flown) missions could alter NASA's selection of future missions altogether. Moreover, the further out one looks, the uncertainty increases about a mission's value and its science and technology content.

1.3 Role of Real Options in NASA Strategic Planning

The real options framework confers some true advantages for NASA in its strategic planning (over other methods for selecting technology investments such as net present value). The real options framework values technology investments by taking into account the flexibility they can offer in the face of considerable uncertainty. NASA, as the holder of these real options, can decide to invest in missions, wait, divest, or change missions in response to better information as some of these uncertainties are resolved. In simplest terms, the real options framework captures the additional value inherent in some technologies that currently goes unrecognized in the NASA budgeting process. Using the real options framework, NASA can achieve greater strategic flexibility with its limited technology budget.

2.0 Real Option Value for NASA Technologies

The value v of a real (non-income producing) option that pays off $W(T)$ at time T is given by the general formula:

$$v(t,T) = \exp(-r(T-t))\mathrm{E}[\max(0, W(T))] \qquad (1)$$

where t is current time, E denotes expected value in a risk-neutral world, and r is the riskless discount rate. The application of this equation to NASA technology evaluation was elaborated by Shishko [1997], where it was needed to explicitly treat the technology's development cost and probability of success. The development cost was treated as a required payout whose amount was uncertain. The expected development cost was calculated over all (proposed) paths leading to TRL = 6, and then discounted appropriately. Thus, the first risk-neutral expectation, E[ ], in Eq. (2) is taken over technology development outcomes, while the second is taken over "states of the world" in which different mission sets are realized.

$$v_i(t,T) = \max\left(0, -\sum_{\tau=t}^{T} \mathrm{E}[c_i(\tau)\exp(-r(\tau - t))] + p_{i,T} \sum_{\tau=T}^{T^*} \mathrm{E}[X_i(\tau)\exp(-r(\tau - t))]\right) \quad (2)$$

where

$$X_i(\tau) = \sum_k X_{i,k}(\tau) = \sum_k \max(0, VMP_{i,k}(\tau) - MC_{i,k}(\tau))$$

and

$v_i(t,T)$ = the option value of technology i at time t for a technology readiness date of T

r = the riskless discount rate

$c_i()$ = the development cost of technology i for a technology readiness date of T

$p_{i,T}$ = the probability that the technology i development program will be successful by the technology readiness date, T

$X_{i,k}$ = the net marginal value of the technology i in project/mission k, given a successful technology i development program

$VMP_{i,k}$ = the value of the marginal contribution of technology i in project/mission k, given a successful technology i development program

$MC_{i,k}$ = the marginal cost of "productizing" technology i in project/mission k, given a successful technology i development program

T^* = the time horizon ($T^* \geq T \geq t$).

The form of Eq. (2) is tied to the earlier discussion about the tradeoff surface among T, $p_{i,T}$, the expected cost of reaching TRL = 6, and the achieved level of technical performance following development. We essentially chose to hold T and the achieved level of technical performance constant, while allowing the probability of development success and cost to vary concomitantly. Another approach would be to hold T constant, set the probability of development success equal to one, while allowing the achieved level of technical performance and cost to vary concomitantly. Whether the achieved level of technical performance is treated stochastically or not, $X_{i,k}$ is conditional on its state at time T.

2.1 Black-Scholes Implementation

If one makes a number of simplifying assumptions that were described by Fisher Black and Myron Scholes, it is possible to obtain an exact easy-to-apply formula for Eq. (2). This Black-Scholes implementation can be explained with a simple decision tree and the option value of the technology is determined by a risk-neutral calculation of the tree's present value.

The Black-Scholes equation is easily applied, but the underlying assumptions of the Black-Scholes implementation may not be true in this application. Until some experience has been accumulated, it is prudent to capture the underlying uncertainties more directly through Monte Carlo simulation and decision trees. When a sample of technologies has been treated this way, it may be possible to test whether the Black-Scholes equation is sufficiently accurate for application within NASA.

2.2 A Proposed Implementation for NASA

Monte Carlo simulation is the natural tool for approximating the expected values in Eq. (2). Today, the computational intensity of Monte Carlo simulation tends to be driven by the complexity of the behavioral models using the stochastic variables. For NASA technology investments, the behavioral models for the underlying asset (i.e., mission) value are likely to be even less complex than in the financial world. Computational time is, therefore, unlikely to be a problem.

NASA technology program managers like to classify technologies as either *cost-reducing*, *mission-enhancing*, or *mission-enabling*. In implementing a real options approach for NASA, we would like to have a common framework so that each of these three cases is just a specialized application of the framework. We first define each of these cases:

Table 2—Technology Cases Definitions

Case	Definition
Cost-Reducing	Results in a reduction in the cost of a mission without changing its value
Mission-Enhancing	Results in an increase in the value of a mission with or without changing its cost
Mission-Enabling	Results in an ability to perform a mission that was previously not possible at any cost, with mission value remaining unchanged; mission-enabling is an extreme form of a cost-reducing case.

For our common framework, we draw on the work of Trigeorgis [1996] on real options. Consider a generic two-period framework in which the perceived value of a particular mission in the second period could be either higher (denoted by a + superscript) or lower (denoted by a – superscript) than initially perceived. Let $V_{i,k}$ be the future value of mission k with technology i, and $V_{\sim i,k}$ be the future value of mission k without the technology. The uncertainty in the future value of the mission is of course just what is captured in the Black-Scholes equation in a different way by assuming a Weiner process. Denote the value of the marginal contribution of technology i in mission k as $VMP_{i,k} = V_{i,k} - V_{\sim i,k}$, Next, let $C_{i,k}$ be the cost of mission k with technology i, and $C_{\sim i,k}$ be the cost of mission k without the technology, then the marginal cost of productizing technology i in the mission is $MC_{i,k} = C_{i,k} - C_{\sim i,k}$.

The two decision trees in Figures 2a and 2b represent what can happen. The decision tree in Figure 2a represents a world in which technology i is not developed. The decision tree in Figure 2b represents a world in which the development of technology i is attempted for potential use on mission k. Technology i need not be inserted in mission k, if it turns out to be better to use another (existing) technology. Within this simple framework, if mission k flies, the expected payoff of mission k (without technology i) discounted to the first period using the riskless rate **plus** the option value of technology i in mission k must be the larger of the two decision trees' root payoffs also discounted to the first period using the riskless rate, r.

$$\left(\pi V^{+}_{\sim i,k} + (1-\pi)V^{-}_{\sim i,k}\right)/(1+r) + v_{i,k}$$
$$= \max\left(\begin{array}{l} \pi V^{+}_{\sim i,k} + (1-\pi)V^{-}_{\sim i,k}, \\ -(1+r)\mathrm{E}[c_i] \\ + p\left[\pi \max(V^{+}_{\sim i,k}, V^{+}_{i,k} - \mathrm{E}[MC_{i,k}]) + (1-\pi)\max(V^{-}_{\sim i,k}, V^{-}_{i,k} - \mathrm{E}[MC_{i,k}])\right] \\ + (1-p)\left[\pi V^{+}_{\sim i,k} + (1-\pi)V^{-}_{\sim i,k}\right] \end{array}\right)/(1+r)$$

Hence:

(3)

$$v_{i,k} = \max\left(0, -(1+r)\mathrm{E}[c_i] + p\left[\pi \max(0, VMP^{+}_{i,k} - \mathrm{E}[MC_{i,k}]) + (1-\pi)\max(0, VMP^{-}_{i,k} - \mathrm{E}[MC_{i,k}])\right]\right)/(1+r)$$

where π is the risk-neutral probability that allows expected values to be discounted at the riskless rate; p is the probability of development success for technology i, and $E[c_i]$ is the expected development cost for technology i, which is incurred in the first period. (The subscripts i,k on π and the subscripts i and T on p have been suppressed for readability.)

Equation (2), which should be used in practical applications of the option-pricing approach for NASA, is just a multi-mission, multi-period elaboration of Eq. (3). Each of the technology cases is discussed in the following sections, using Eq. (3) as a didactic tool.

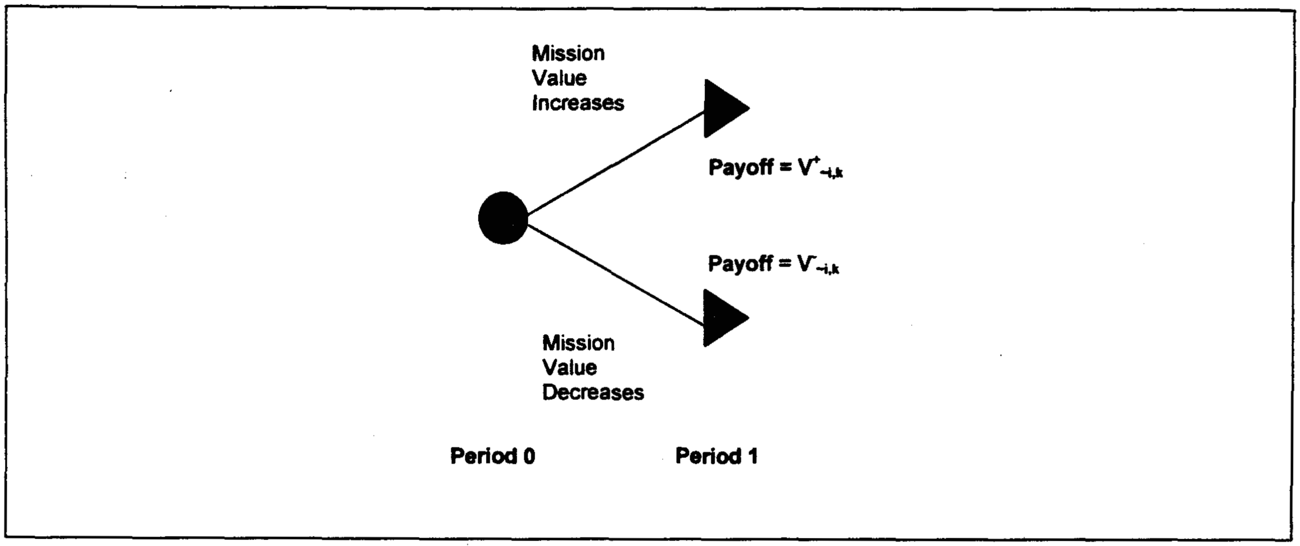

Figure 2a—Simple Decision Tree Without Technology Development

2.2.1 When A Technology Is Cost-Reducing

In the cost-reducing case, Eq. (3) takes a much simpler form because by definition $V^{+}_{i,k} = V^{+}_{\sim i,k}$ and $V^{-}_{i,k} = V^{-}_{\sim i,k}$. Since $E[MC_{i,k}] < 0$, the option value reduces to:

$$v_{i,k} = \max(0, -\mathrm{E}[\Delta I])/(1+r) \qquad (4)$$

where $\Delta I = p\, MC_{i,k} + c_i\,(1+r)$ is the additional investment required by technology i in mission k. Equation (4) states that the option value is simply the discounted value of the expected cost savings from a successful development of technology i times the probability of development success less the expected development cost. The risk-neutral probabilities, which capture the uncertainty in the future value of mission k, disappear from the technology option pricing formula. This comes from the assumption (embedded in the definition of the cost-reducing case) that technology i has no effect on the uncertainty in the mission's future value (i.e., its market risk). Since Eq. (3) was conditional on the mission flying, one must fold in the probability that mission k actually flies in order to complete the option value calculation.

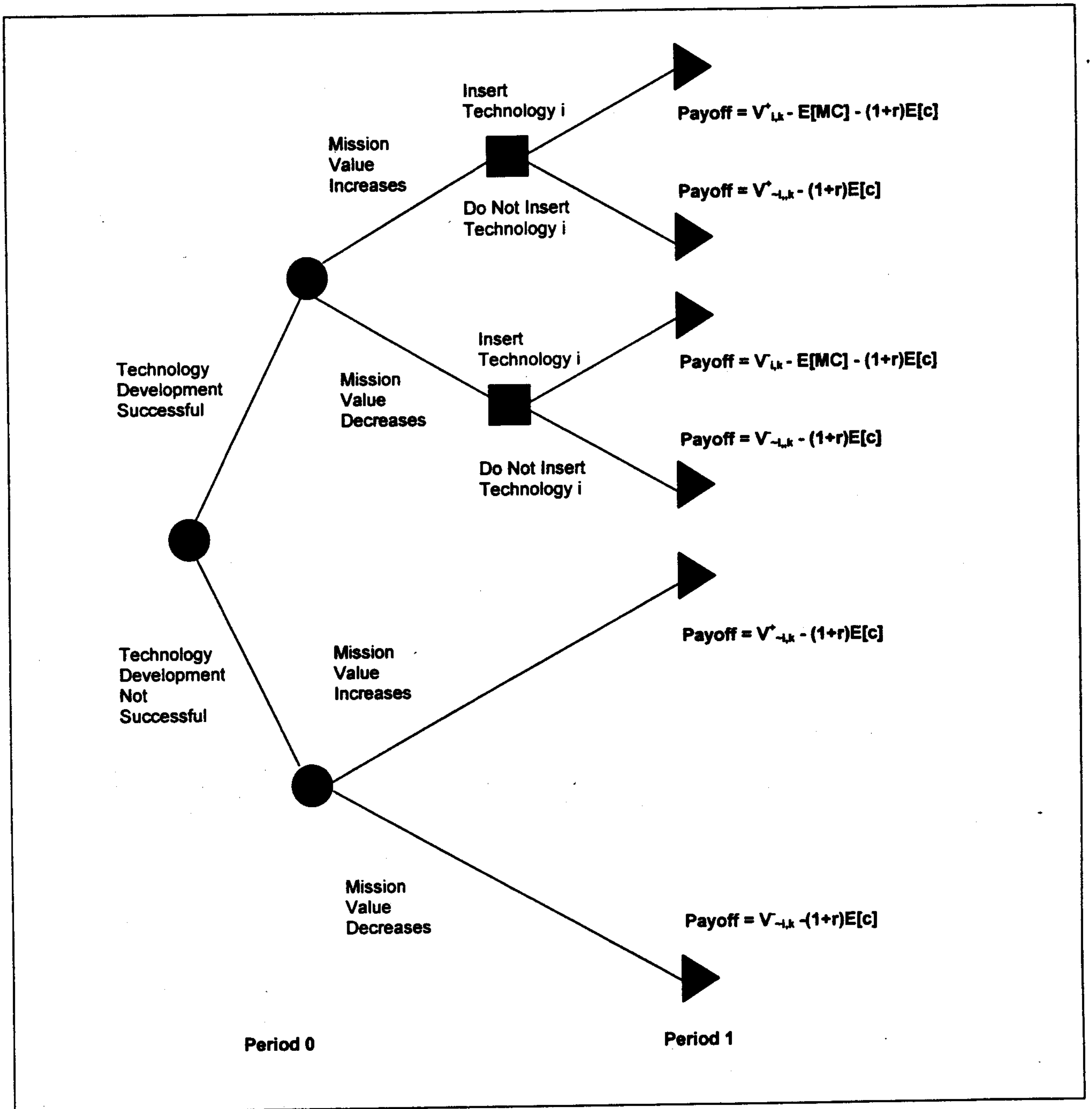

Figure 2b—Simple Decision Tree With Technology Development

Equation (2) also takes a simpler form in the cost-reducing case, but the results are identical. The expected payoff, $E[X_{i,k}]$, for a single mission is just $-E[MC_{i,k}]$ as $V_{i,k} = V_{\sim i,k}$ (i.e., $VMP_{i,k} = 0$). The option value calculation using Eq. (2) also requires that the expected development cost be subtracted from the expected payoff and that both of these be discounted at the riskless rate. The practical application of Eq. (2) requires that these expected values can be calculated for real missions. Procedures for each of these are covered below.

Expected Development Cost and Probability of Success. The procedure for calculating the expected development cost consists of a series of temporally spaced data elicitation interviews employing visual aids. The steps are:

1. Prepare for the data elicitation interview;
2. Interview technology manager re: technology status, steps required to bring technology to TRL=6, identifying uncertainties in program, and alternatives if failures were to occur;
3. Prepare influence diagram and rudimentary decision tree;
4. Re-interview technology manager re: influence diagram's and decision tree's representation of development path, costs, and probabilities at each node;
5. Complete decision tree;
6. Run decision tree calculations (using Monte Carlo simulation, or discrete approximations for continuous distributions, if less accuracy will suffice) to obtain the distribution of development costs and probability of development success.

This procedure forces technology managers to have a clear plan (with contingencies for unmet milestones) for reaching say, TRL = 6. We developed and validated sample decision tree models for several Mars exploration technologies using this procedure, one of which (*low temperature and mass propulsion technology*) is shown in Figure 3. The tree shows all of the paths leading to TRL = 6, from which the probability of development success could be ascertained. The decision tree effectively breaks down the technology development into smaller steps so that uncertainties can be explicitly identified and quantified.

Expected Payoff. An estimate of $E[MC_{i,k}]$ can be computed using Monte Carlo methods. Typically, mission costs are estimated during early conceptual studies using a set of *cost estimating relationships* (CERs)—one CER for each spacecraft subsystem plus wraparound factors for integration and test, systems engineering, and project management. Additional CERs or other models are used to estimate mission design, mission operations development, project science, launch vehicle procurement, and mission operations costs. Altogether, these cover mission life-cycle cost.

Spacecraft CERs are usually estimated using multiple regression techniques on historical cost data. As such, each subsystem's estimated cost has some uncertainty associated with it. However, the distribution of each subsystem's estimated cost is known, and can be used in a Monte Carlo estimate of the total cost. The technology, for which the option value is being calculated, will generally affect one or more subsystems. This influence results in changes to the CER's input values for those subsystems. If a CER for a particular subsystem is deemed to be invalid for a new technology, then that subsystem CER may need to be replaced altogether in order to run the Monte Carlo.[3]

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[3] We think that for many technologies the new CER for the Monte Carlo analysis will likely be constructed by a team of engineers and cost risk analysts. One procedure involves the elicitation of a cost probability density function (by well-known techniques) from the team. This method is preferred because it is tailored to the new technology in question. Another procedure, outlined in Wertz and Larson (eds.), *Reducing Space Mission Cost*, pp. 261-263, assigns the parameters of a lognormal distribution based on the technology's TRL.

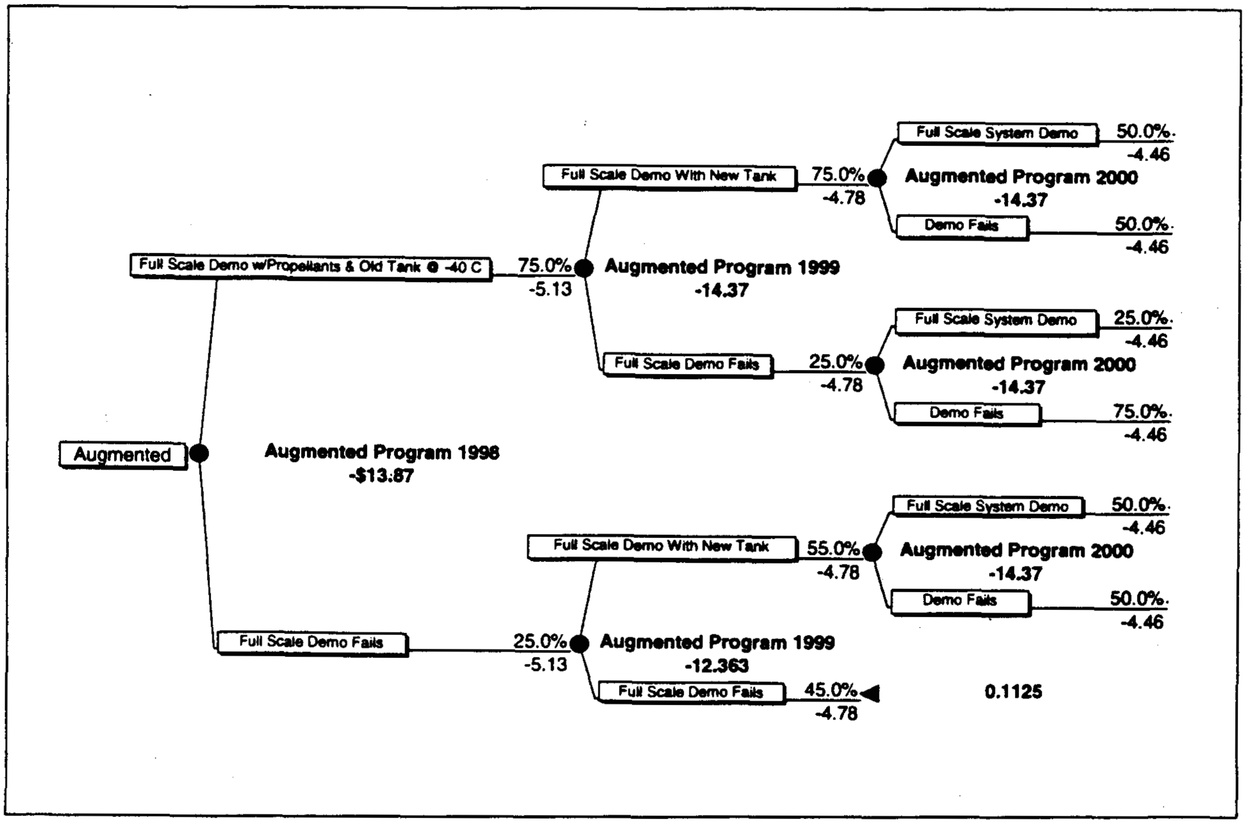

Figure 3—Development Decision Tree For Low Temperature/Mass Propulsion Technology

The Monte Carlo simulation, of which the cost savings are a part, also needs to consider whether the mission is actually flown. Whether a particular future mission is flown depends on many factors. These factors include the size of the NASA budget in the period leading up to the mission's formal approval and the success or failure of earlier related missions. Unanticipated, even serendipitous, scientific discoveries on other missions could alter NASA's desired mission sets. The total estimated cost of a mission could play a role in determining whether it flies or not, as demonstrated by the Human Exploration Initiative in 1989. Our recommendation for incorporating these considerations in the process is to use expert judgment to quantify the probability that a particular mission flies. This expert elicitation should make a distinction between roadmapped missions—missions selected by various science committees as critical—

and those that are not roadmapped. The probability that a particular mission flies to be elicited by expert judgment is then conditional on this knowledge.[4]

The probability so supplied has the effect of reducing the payoff calculated by the Monte Carlo procedure above (as a part of the overall Monte Carlo calculation being made to value the technology option). *However, it also has the effect of allowing any potential mission to contribute to the overall option value.* The cumulative effect can be substantial. Making the probability that a particular mission flies explicit is, in itself, an improvement. It separates the technical calculations of the Monte Carlo, which are based on engineering and cost relationships, from the programmatics portion.

2.2.2 When a Technology is Mission-Enhancing

In the mission-enhancing case, Eq. (3) cannot be simplified unless some additional assumptions are made for mission k. We first note using Eq. (3) that if $E(\Delta I)$ exceeds both $V^+_{i,k}$ - $V^+_{\sim i,k}$ (i.e., $VMP^+_{i,k}$) and $V^-_{i,k}$ - $V^-_{\sim i,k}$ (i.e., $VMP^-_{i,k}$), then the option value of technology i in mission k is zero. Basically, this means that if the mission value isn't enhanced enough by technology i to cover the expected additional investment under any scenario, there is no value to the technology option. However, Eq. (3) illustrates the assertion that when there are scenarios in which a technology can potentially add to the value of a mission using that technology, then that technology's option value may attain a high positive value.

Next, we note that when $VMP^+_{i,k}$ = $VMP^-_{i,k}$, then the risk-neutral probabilities again disappear:

$$v_{i,k} = \max(0, -(1+r)\mathrm{E}[c_i] + \dot{p}\max(0, VMP_{i,k} - \mathrm{E}[MC_{i,k}])/(1+r) \qquad (5)$$

[4] Miles (1998) has demonstrated techniques at JPL to obtain a probability density function for a subjective number like this using multiple experts.

This condition does not say that the uncertainty in the mission's future value (i.e., its market risk) is gone, only that the mission enhancement provided by technology i is the same across all scenarios. From Eq. (3), when $VMP^{+}_{i,k} \neq VMP^{-}_{i,k}$, risk-neutral probabilities are needed in addition to expected development costs, the probability of development success, and any expected savings (either positive or negative) from using technology i.

For the simplified option valuation model considered here, constructing VMP depends on being able to project the mission's possible future values at a point in time both with and without the mission-enhancing technology. Consensus expert judgment appears to be the most reasonable procedure for projecting mission value for each possible discrete future state/technology alternative. Such judgment would include an indication of the physical probabilities of alternative future mission values.

Calculating the risk-neutral probabilities corresponding to alternative future mission values depends on being able to specify a portfolio of value-producing assets which replicates the future state mission values. When considering real option valuation in the private sector, those value-producing assets are typically a portfolio of riskless and risky securities projected to respond in the future period so as to replicate the value of the private sector project. In principle there is no restriction to securities. For example, the portfolio could also contain alternative value-producing assets, such as private sector projects, for which it is possible to assert credible future state values under the conditions assumed when projecting future state mission values. See the Appendix for a proposed method for computing the risk-neutral expected value of $X(\tau)$ when it is impractical to identify explicitly the underlying future risk states (corresponding to the π_i's).

2.2.3 When a Technology is Mission-Enabling

In the mission-enabling case, the cost of the mission without technology i is essentially infinite, rendering its option value (using Eq. (3)) implausibly infinite as well. To establish the technology's option value, we first define the "reservation price" for mission k, R_k, as the lowest price at which society's demand for mission k is zero. The future reservation price for mission k is uncertain, just as its future value is. The future reservation price could be either higher (denoted by a + superscript) or lower (denoted by a – superscript). By definition of the mission-enabling case, the future value of mission k is unaffected by the choice of technology, so $V^+_{i,k} = V^+_{\sim i,k} = R^+_k$ and $V^-_{i,k} = V^-_{\sim i,k} = R^-_k$. We next substitute the appropriate R_k for $C_{\sim i,k}$ in Eq. (3) to obtain:

$$v_{i,k} = \max\left(0,-(1+r)\mathrm{E}[c_i] + p\left[\pi \max(0, R_k^+ - \mathrm{E}[C_{i,k}]) + (1-\pi)\max(0, R_k^- - \mathrm{E}[C_{i,k}])\right]\right)/(1+r) \quad (6)$$

If $E[C_{i,k} + (1+r)\, c_i]$ exceeds the larger(est) reservation price, then the option value of technology i in mission k is clearly zero. *A fortiori,* if $E[C_{i,k}]$ exceeds the larger(est) reservation price, then the option value of technology i in mission k is also zero. Indeed an implicit assumption for the validity of Eq. (4) in the cost-reducing case (Section 2.2.1) was that the reservation price equals or exceeds both $E[C_{i,k}]$ and $E[C_{\sim i,k}]$.

Expert judgment appears to be the most reasonable procedure for projecting reservation prices for a given mission with a mission-enabling technology. Since the reservation price for a mission bounds the willingness-to-pay for the mission under alternative future states, elicitation of such information should be a reasonably direct collation of available information using multiple experts. A procedure that has been successfully employed in similar situations is described in Shishko and Ebbeler [1999].

A neutral individual who has experience in probability elicitation should conduct the interview. The experts themselves should be informed non-advocates. In our experience, the interview process is aided by software that displays the rough PDF for each interviewee, since this will often lead an expert to make some revisions. It may also help to re-interview an expert several days later to provide further confirmation that the PDF represents the expert's considered view.

2.3 Multiple Technologies on a Single Mission

Up to now, we have treated each technology as a real option, but the arguments and calculations in this paper could just as readily be applied to packages of cost-reducing and mission-enhancing technologies with a single technology readiness date, *T*.[5] If there are N such technologies that could be pursued, there are in effect $2^N - 1$ possible real options with a given technology readiness date.

When several cost-reducing and mission-enhancing technologies can be applied to a single mission, the option value for each such technology is calculated in isolation—that is, as if only that technology is being applied. Naturally over time, as newer technologies are introduced so that for example $C_{\sim i,k}$ is revised, the option value of the remaining undeveloped technologies must be revised as well. This would normally take place during NASA's periodic technology budget reviews. Our point here is that no complications are introduced by way of Eq. (2) when several cost-reducing and mission-enhancing technologies can be applied on a single mission.

A complication arises with multiple technologies on a single mission when one or more of those technologies is "mission-enabling". If a given mission requires enabling technologies, then that collection of enabling technologies must be considered as a package when calculating

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[5] In general, the option value of a package of two or more of these technologies would not necessarily equal the sum of the option values of its constituents. Additivity would require a combination of offsetting effects unlikely to occur in real-world technology developments.

option value. When the package contains more than one enabling technology, it is only the package that has an option value for that mission, not the individual enabling technologies. Option values for a cost-reducing technology, mission-enhancing technology, or mission-enabling technology package are computed by summing across individual missions that may use the technology or technology package. However, when a mission includes a mission-enabling technology package, the option value for any cost-reducing or mission-enhancing technology associated with that mission is necessarily dependent on the probability of successful development of the mission-enabling technology package.

For example, suppose that a particular cost-reducing technology i impacts three missions. For missions 1 and 2 there are no mission-enabling technologies required, but for mission 3 a mission- enabling technology package, technology package k, is needed. Referring to Eq. (2), $X_i(\tau)$ is the net marginal value of technology i for $T_i \le \tau \le T^*$. Then:

$$X_i(\tau) = X_{i,1}(\tau) + X_{i,2}(\tau) + X_{i,3}(\tau)\delta_{k,3}(\tau) \qquad (7)$$

where

$$\delta_{k,3}(\tau) = \begin{cases} 0 & \text{for } \tau < \max(T_i, T_k) \\ p_k(T_k) & \text{for } \tau \ge \max(T_i, T_k) \end{cases}$$

$X_{i,m}(\tau)$ is the net marginal value of technology i in the m$^{\text{th}}$ mission, given a successful technology i development program, and $p_k(T_k)$ is the probability that technology package k will be ready by the technology readiness date T_k.

3.0 Calculations Using the Mars Sample Return Technologies

The Mars Sample Return (MSR) mission's objective is to collect well-selected samples of Martian soil, rocks, and atmosphere and return them to Earth for detailed scientific analyses. Interest in the MSR mission was sparked by the discovery of structures in a Martian meteorite retrieved from Antarctica in 1984 that some scientists have interpreted as evidence of past biological activity. MSR has public support because it may provide some answers to questions about whether Mars harbors or harbored life.

Two technologies have TRLs < 6. One, *low temperature and mass propulsion*, was identified as cost-reducing and the other, *autonomous Mars-orbit rendezvous and docking*, as mission-enabling for a number of plausible MSR architectures. In this section, we calculate the option values of these technologies.

The MSR is a difficult mission even without having to develop enabling technologies. First, in 2003, a lander spacecraft containing one advanced rover and one Mars ascent vehicle (MAV) will set down on Mars and deploy the rover. The rover will collect samples over a period of time and transfer them to a canister on the ascent vehicle. The ascent vehicle is then launched and places the valuable canistered samples in Mars orbit, where they remain for several years. A low temperature and mass propulsion system for the ascent vehicle (Technology 1) will reduce cost since a smaller spacecraft can be used. Next, in August 2005 using a large rocket, a dual spacecraft is launched from Earth. One part of the dual spacecraft is nearly identical to the one launched in 2003. It performs the same function so that a second canister containing samples (from a different site) is also placed in Mars orbit. The second part of the dual spacecraft contains the Earth-return stage. It must autonomously rendezvous and capture the separate canisters (Technology 2) before beginning its homeward journey.

These technologies must reach TRL = 6 not later than three years before their respective launches, so we take 2000 as the option expiration date for Technology 1 and 2002 as the option expiration date for Technology 2. The MSR 2003/2005 mission will be the first mission to use the technologies. However, other fairly identical MSR missions are also planned for 2007/2009 and 2011/2013. The option value must take in account the contribution of the technologies to these follow-on missions. Potentially other missions—including a manned mission to Mars—might use the technologies, but we will not include these contributions in our calculation.

We selected these technologies for several reasons. First, illustrating the options-pricing approach for the cost-reducing technology case is computationally straightforward and economically intuitive. Second, illustrating the approach using a mission-enabling technology is probably the most difficult of the three cases, and we surmise for NASA managers, the most interesting. In the MSR mission, we immediately ran into a problem that is likely to occur often. NASA programs are a series of related missions designed to address common scientific questions. Each mission within a particular program builds upon previous ones, so their values may be correlated. We needed to address this problem within our options-pricing framework.

3.1 Option Value Calculation for Technology One

The essential information items needed to calculate the option value for the low temperature and mass propulsion technology were the development cost distribution, the probability of development success, and the distribution of savings resulting from a successful development.

In this particular technology, the technology manager provided an initial programmatic choice between a "core program" and an "augmented program." The augmented program had higher upfront costs, more risk, but an earlier *technology readiness date* (2000 versus 2002). (When this occurs, two option values need to be calculated as different dates, probabilities of development success, and distributions of development costs are involved, even if the expected payoff is the same.) The decision tree in Figure 3 shows how risky the augmented program was—the probability of development success was only 0.397—but it was the only credible program that achieved TRL = 6 by 2000. The distribution of development costs was also calculated from the decision tree. Typically, technology development dollars are committed for short periods of time roughly coordinated with development milestones. A development program will be terminated if it is successful, or if several milestones are missed or have unsuccessful outcomes. In this kind of environment, the development cost cumulative distribution function (CDF) tends to be a step function.

The cost savings for Technology 1 were estimated using the JPL Parametric Mission Cost Model based on the dry mass savings of 20 kg per MAV provided by the MSR team. The direct mass savings have indirect effects on the structure, propulsion, and Mars entry subsystems of the lander, as well as on overall project reserves. These effects and their uncertainties were combined, giving a probabilistic cost saving in \$FY99M equal to $2.94 + 1.125\ X$, where $X \sim$ *triang*(0, 2.5, 0.7) and *triang(a, b, m)* represents a triangular distribution over [a, b] with mode, m. The resultant expected cost saving was \$4.14M per MAV/Lander.

Cost savings for each MAV/Lander were spread over the MAV/Lander development period in accordance with accepted NASA "spreader functions." The stream of technology development costs and MSR development savings were then discounted at the riskless rate and combined with the probability of development success in Eq.(2) to compute the Technology 1 option value.

The cost savings (even over six MAVs) were insufficient to obtain a positive option value even if the probability of development success (by 2000) had been one. Figure 4 is one way to show the robustness of this result. At the estimated probability of development success, the expected savings per MAV/lander would have to be about 2 ½ times larger to yield a positive option value.

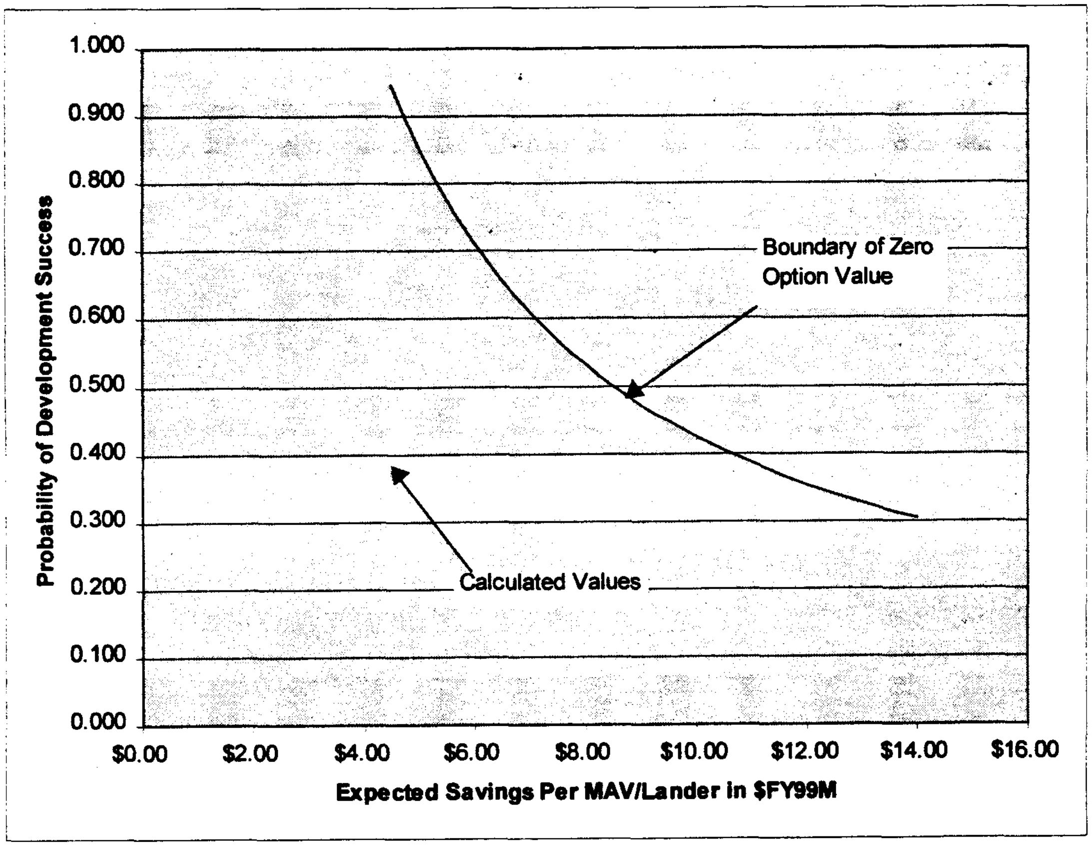

Figure 4—Tradeoff of Expected Savings and Development Success for Low Temperature/ Mass Propulsion Technology

3.2 Option Value Calculation for Technology Two

Four experts were interviewed to obtain probability distributions. Each expert was asked first to provide the probability distribution for the reservation price of the first MSR mission in 2003/2005. Next they were asked to provide the probability distributions for the reservation price of the second and third MSR missions. These distributions were to consider the range of potential outcomes of any earlier MSR missions, as for example, finding evidence of past life on Mars. The experts confided their respective rationales, which were surprisingly different. Nevertheless, we combined the individual distributions into a single one by the simplest method recognized in the literature:

$$p(\theta) = \sum_{i=1}^{n} w_i p_i(\theta) \tag{8}$$

where n is the number of experts, $p_i(\theta)$ represents expert i's probability distribution over unknown parameter, θ, and w_i are non-negative weights that sum to one. We weighted the experts equally to obtain the combined CDF shown in Figure 5 for the first MSR mission. The method described in Shishko and Ebbeler [1999] was used to allow the sequential Monte Carlo sample to have a correlation structure that we could control parametrically.

The JPL Mars Program Office estimated expected mission costs for MSR 2003/2005 (excluding launch costs). For the Monte Carlo simulation, we used a Normal distribution with a standard deviation sufficient to cause an overrun of 15 percent, which triggers a NASA cancellation review, approximately once in 40 trials (2.5 percent of the time). We also assumed that MSR 2007/2009 and MSR 2011/2013 will cost 70 percent (in constant dollars) of the MSR 2003/2005 mission. The budget for MSR 2003/2005 revealed that a second set of major mission elements (lander, MAV, and rover) would cost 50.2 percent of the first set. Thus, a 70 percent estimate can be considered realistic, if no major design changes are introduced. Lastly, launch costs for all three missions were treated non-stochastically since these costs are fixed in advance. During the Monte Carlo simulation, sampled costs and correlated reservation prices for each trial were dropped into a simple spreadsheet that spread the costs over the period from FY99 through FY16. These were then discounted using the riskless discount rate. To calculate the option value, we combined these discounted results with the probability of development success and the discounted expected technology development cost, both of which were derived from the

Technology 2 development decision tree. This probability was .638, while the expected technology development cost was $12.54M ($FY99).[6]

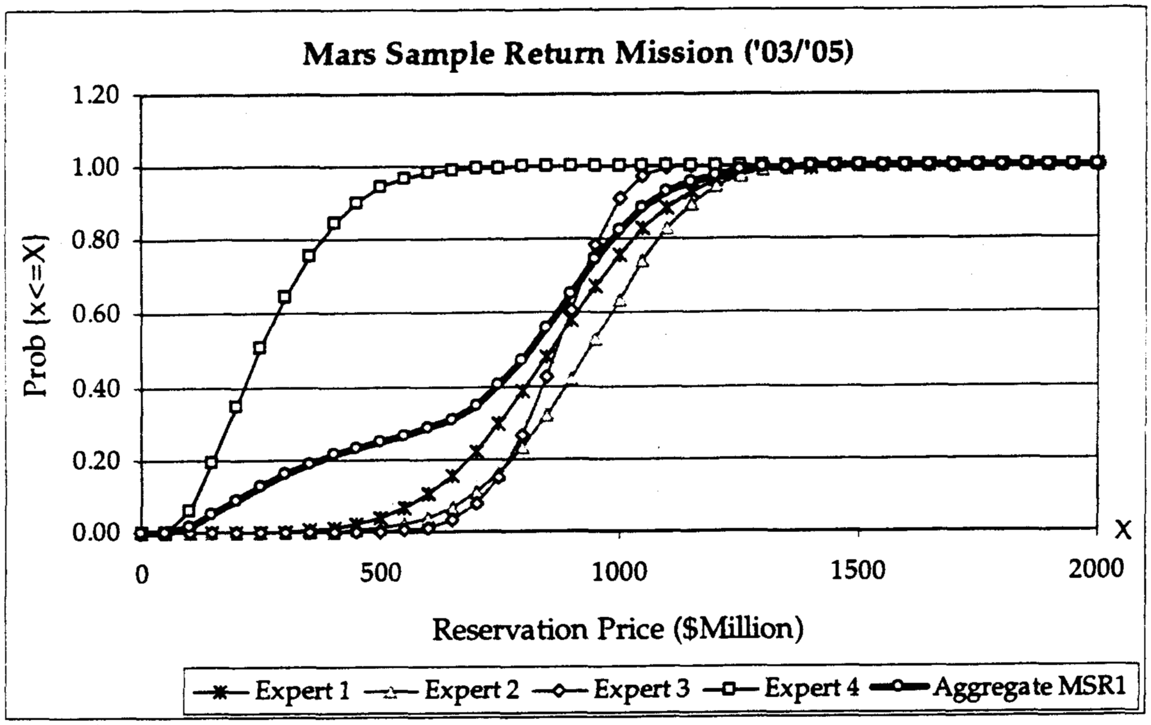

Figure 5—Individual and Combined CDFs for MSR 2003/2005

The option value for Technology 2 using Eq. (2) was $32.56M ($FY99) based on 10,000 Monte Carlo trials and a correlation structure with high pairwise correlation coefficients (ρ_{ij} = 0.95, in this case). The distribution of option value outcomes is shown in Figure 6 along with that for the corresponding Net Present Value (NPV).

The expected values of the two distributions imply conflicting recommendations. The NPV approach rejects this technology development, while the option-pricing approach favors it. The option value represents how much NASA should be willing to pay for the "rights" to

[6] The probability of development success is a project-specific risk, not a market risk. We agree with Smith and Nau [1995] that such risks ought to be treated using physical probabilities rather than the risk-neutral probabilities appropriate for handling market risks.

undertake the proposed Technology 2 development program. The difference in value between the two approaches is the result of managerial flexibility and the strategic importance of the Technology 2.

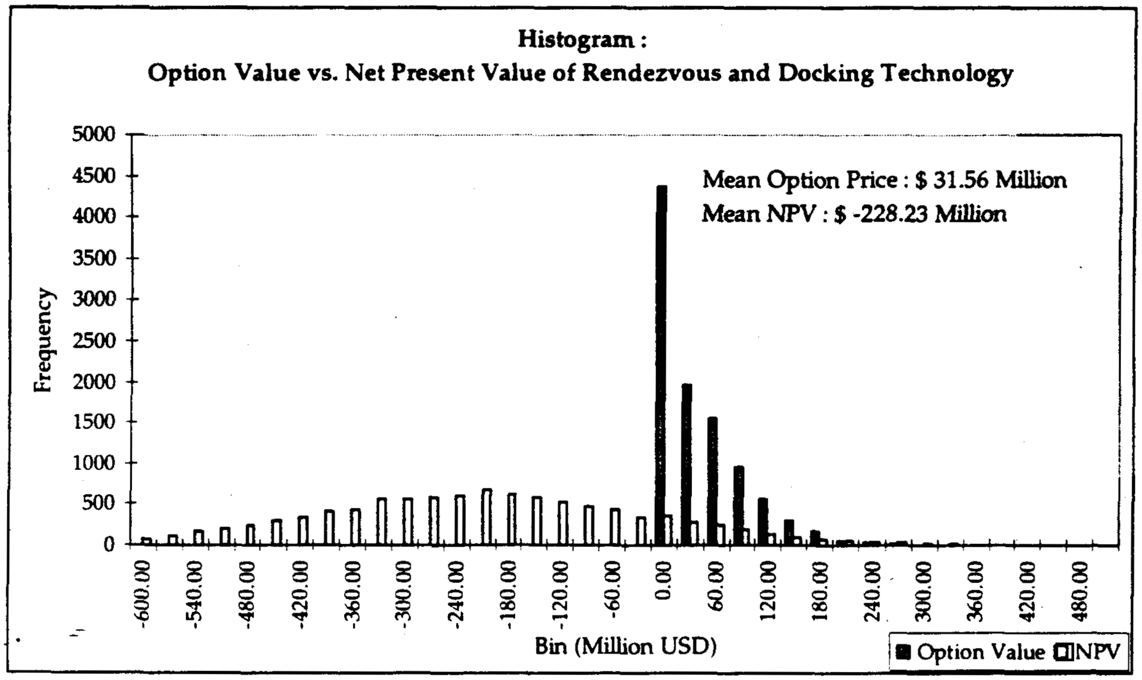

Figure 6—Distribution of Outcomes for Option Price and NPV

NASA has committed to "fly" MSR 2003/2005, but it is not committed to fly the follow-on missions in the series. Suppose that the scientific results from this first mission are disappointing and the reservation prices for the second and third missions in the series are highly positively correlated with that for the first. Society's (re-evaluated) reservation price for follow-on missions would tend to be low as well. In spite of a high correlation, the traditional NPV approach assumes the follow-on missions would fly; but in the options approach, NASA management could opt to abandon the follow-on MSR missions and use the resources for more highly-valued missions.

Another reason for the relatively high value is that Technology 2 is the last of the MSR mission-enabling technologies with TRL < 6. It is, in a nutshell, the last remaining technology obstacle to a set of strategically important NASA missions! In general, as individual enabling technologies in a package are successfully developed, acquire TRL = 6 status and hence drop out of the package, the option value for remaining mission-enabling technologies in that package grows. Part of the reason is that the remaining expected development cost for the package decreases and the remaining overall probability of development success increases.

3.3 Effect of Alternative Correlation Structures

We investigated the effect of alternative correlation structures as part of this research. The option value fluctuated between $31.1M and $35.2M depending on the correlation coefficients. When all of the coefficients were set to zero, implying that the distributions describing the reservations prices of the three missions in the MSR series were uncorrelated, the option value attained its minimum level. When the three coefficients were set to one, implying that the distributions describing the reservations prices of the three missions in the MSR series were perfectly correlated, the option value was $32.7M. The maximum option value was reached when the correlation coefficients were all set to 0.6.

4.0 Issues and Summary

4.1 Public Goods and the Options-Pricing Approach

Much of the theoretical foundation for the option-pricing approach for valuing real projects lies in the idea of being able to replicate that project in a portfolio of riskless and risky securities so that risk-neutral probabilities can be calculated. *Replication* here means creating the identical payoff (monetary outcome) in each future state. Any difference between the "selling" price of the project and the value of the replicating portfolio would create an immediate riskless arbitrage opportunity. An open question is whether assembling a replicating portfolio for most NASA R&D projects is any more difficult than for high-risk R&D projects in the private sector.

Perhaps some NASA projects are so risky that a replicating portfolio cannot be found. For now, we appeal to the arguments used by Smith and Nau [1995] that allow extension of the option-pricing approach to incomplete and partially complete markets. In valuing NASA projects, then, one should use risk-neutral probabilities for market-based uncertainties; and one should rely on subjective probabilities of appropriate experts for those uncertainties that are project-specific.

A separate, though related, issue concerns whether NASA (as a government agency) should be risk-neutral altogether without regard to whether uncertainties can be hedged or not. Does the public goods aspect of NASA investments make the case that NASA should be risk-neutral in valuing its R&D projects? This is related to the long-standing debate over what discount rate to use in public investment decisions.

4.2 Summary

In this paper we developed a didactic real options model that led to an option pricing equation for technology developments in which the costs and payoffs are uncertain. In this model, three classes of technologies applicable to NASA were treated as special cases yielding some simplifications that could be exploited. The model could be applied to commercial technology developments as well, by replacing scientific mission value (society's willingness-to-pay) with commercial value (profits).

Next, we demonstrated the feasibility of applying the option pricing approach by showing its application to two Mars Sample Return technologies—*low temperature and mass propulsion* and *autonomous Mars-orbit rendezvous and docking*. In the process we dealt with a number of methodological issues that would be fairly common in wider application, and we raised other issues that await further investigation. One of these is the computation of risk-neutral probabilities for NASA missions, which is made more difficult by the long time horizons involved. We recognize that the application of real options to publicly funded technology developments requires further research and hope that other views will emerge.

Appendix

A technology's option value requires calculation of $\int_0^\infty g(u)x(\tau,u)\exp(-r\tau)du$ where $g(u)$ is the risk-neutral density function obtained by solving $\underline{s}(0) = \int_0^\infty g(u)\underline{s}(\tau,u)\exp(-r\tau)du$. Here, $\underline{s}(0)$ is the current price vector of a portfolio, $\underline{s}(\tau,u)$ is the price vector of the portfolio at time τ under the risk state corresponding to u, and r is the riskless discount rate. $X(\tau,u)$ is the net marginal value of the technology, given a successful technology development program, under the risk state corresponding to u, i.e., $x(\tau,u) = u$. However, the different risk states corresponding to different values of u are typically implicit, so there is no direct way to specify $\underline{s}(\tau,u)$, solve for $g(u)$ and calculate the desired option value.

Instead, consider a collection of real projects and financial assets with the properties: (1) cumulative distribution functions, $F_1(x_1), \ldots, F_k(x_k)$, can be constructed for the same time, τ, and (2) the relationship between values of each x_j and the underlying risk states are known for each element in the collection, so that the risk-neutral density functions $g_j(x_j)$ can be calculated from

$$\underline{s}_j(0) = \int_0^\infty g_j(x_j)\underline{s}_j(\tau,x_j)\exp(-r\tau)dx_j \qquad \text{for } j = 1, \ldots, k.$$

For time τ, a cumulative distribution function, $F(u)$, is obtained for $X(\tau,u)$ as, for example, in Section 3.0 using aggregated expert judgment. $F(u)$ can be approximated as a function of $F_1(x_1), \ldots, F_k(x_k)$, which is realized through a linear approximation of u by $\sum_{j=1}^{k} \lambda_j x_j$ (see Shishko and Ebbeler [1999]). Then, we have $\exp(-r\tau)\mathrm{E}(X) = \exp(-r\tau)\left\{\sum_{j=1}^{k} \lambda_j \mathrm{E}[X_j] + \mathrm{E}[\varepsilon(U)]\right\}$ where $\varepsilon(u)$ is the discrepancy function between u and the linear approximation. This implies $\int_0^\infty ug(u)du = \sum_{j=1}^{k} \lambda_j \int_0^\infty x_j g_j(x_j)dx_j + \mathrm{E}[\varepsilon(U)]$. The k elements should be chosen such that $|\mathrm{E}[\varepsilon(U)]|$ is acceptably small.

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